Simulation of the groundwater flow in hard rock hydrogeological environments. Application in Naxos Island, Greece

Aikaterini-Sofia Partsinevelou, Levkothea Evrenoglou and George Stournaras

Abstract—Groundwater is a dynamic and renewable natural resource, but in hard rock terrains the availability of groundwater is limited. Although it is observed that hard rocks have often low permeability, they may host important water resources [1], as the groundwater flow regime in this case is depended mainly by several factors of the fractured media [2], [3]. Exploration and utilization of groundwater especially in hard rock terrains, requires thorough understanding of geology, geomorphology and lineaments of the area, which directly or indirectly control the terrain characteristics.

There are several methods such as geological, hydrogeological and geophysical to locate and map the occurrence and distribution of groundwater. But recent studies have focused on the remote sensing methods and GIS techniques, as they provide the advantages of having access to large coverage, even in inaccessible areas, and of having an efficient way of mapping the natural resources economically, with better results, than using conventional methods [4], [5]. Temporal remote sensing data enable the identification of groundwater aquifers and assessment of their change, where GIS enables the management and integration of multi-thematic data.

Keywords—Hard rock hydrogeology, FeFlow, AHP Analysis, GIS, Remote Sensing Methods.

I. Introduction

NAXOS Island occupies a central position in the Aegean Sea and it is consisted mainly by schists, gneiss and marbles, which are corresponded to the term "hard rocks". The present study was aimed to identify and delineate groundwater potential areas in hard rock terrains. For this purpose, five factors have been selected based on the main characteristics of these terrains, which are a) the topographic slope, b) the lineaments density, c) the hydrolithology, d) the drainage density and e) the land cover of the study area. The factors were weighted according to AHP analysis. The information of lithology, geomorphology, lineaments, slope and land cover was generated by using topographical and geological maps of scale 1:50.000, land cover data from the Ministry of Agriculture of Greece, aerial photographs and a Landsat 7 ETM+ image of the study area. The integration of all data was made in a raster based Geographical Information System (GIS) to identify the groundwater potential zones. On the basis of hydrogeomorphology, four categories of groundwater potential zones namely very good, good, moderate good and poor were identified, and delineated. The high potential zones correspond to areas with low slope and high lineaments density areas, in contrast with the low potential zones, which act as run-off zones. The derived groundwater potentiality information could be used for a first estimation of the distribution of water infiltration and for effective identification of suitable locations for extraction of potable water for rural populations.

The present study focuses on the identification of groundwater potential areas and the groundwater flow in the hard rock terrain of Naxos Island, using the advanced technology of remote sensing, raster based GIS and the Finite Element Method. The water resources in Naxos Island are extremely limited. Surface water is available only for a few days after heavy rains and the water needs are mainly fulfilled by the groundwater resources. However, groundwater resources are also limited, due to natural and anthropogenic causes, such as the climate, the pollution and abstraction of aquifers, the small water capacity of the geological formations, the high morphological slopes and the low vegetation, which is mainly characterized by the presence of maquis and brushwood [6].

II. The Study Area

Naxos is the largest island of Cyclades and occupies a central position in the Aegean Sea (Fig. 1). Its circumnavigation is equal to 44 nautical miles and its area reaches 430 km2. Naxos is mountainous, having a central mountain range, which crosses the island from the northern to the southern part. The highest altitude is 1001 m, at Zeus peak, located in the central part of the range and it has extremely low precipitation rates [7]. Also, like all the islands of Cyclades, Naxos faces a serious problem of water scarcity, which leads to a continuous interest for searching and exploiting the groundwater resources.

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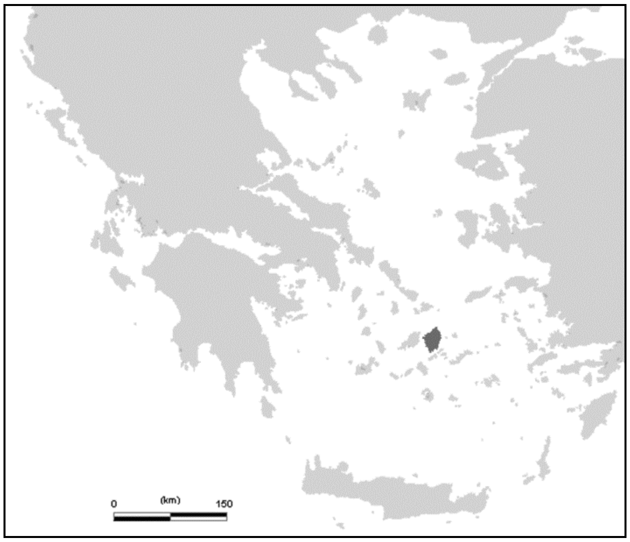

Fig. 1 geographical location of Naxos island in Greece

Geologically, the study area belongs to the Attic-Cycladic Massif (Fig. 2). This massif has been developed by thrust faulting, ductile thinning and normal faulting and it is mainly built up by metamorphic rocks of several metamorphic facies [8]. Naxos Island is described mainly as an elliptic dome with main direction N15^{o}E which is consisted by schists, gneiss and marbles [9].

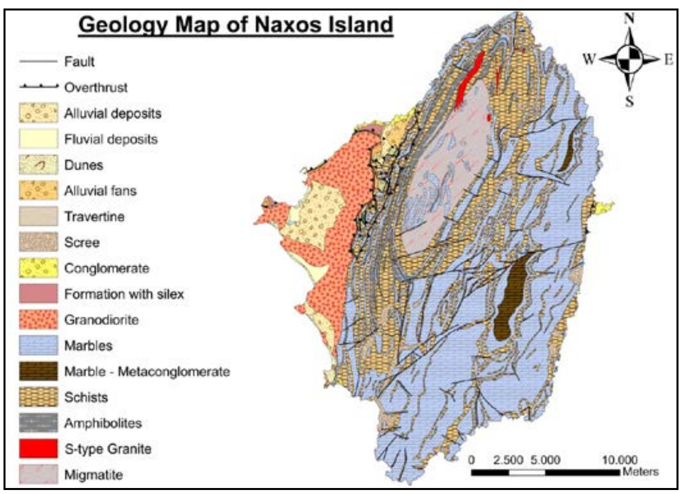

Fig. 2 simplified geological map of Naxos island

In general, the geology of Naxos can be divided into three main units, a) the upper non-metamorphic unit, b) the Cycladic blueschist unit and c) the granodiorite massif [10]. The upper unit is a very thin and non-metamorphosed nappe which is consisted of Miocen e-Pliocene sedimentary rocks and overlies the Cycladic blueschist unit and the granodiorite massif (allochthonous unit). The Cycladic blue schist unit is a metamorphic complex mainly characterized by a migmatite core which is surrounded by a multifolded sequence of marble s, metapelites, schists, amphibolites and gneiss. At the superiorly part of this unit metabauxites and metaconglomerates are appeared. T he granodiorite massif appears at the west of the island and it is consisted of an I-type granite which intrudes the Cycladic blueschist unit . Both the Cycladic blueschist and the granodiorite unit constitute the autochonous unit of the island. Also undeformed intrusives, mainly S-Type granites, are found in the northern part of the island [11].

III. Methodology

In order to define and delineate the groundwater potential areas in Naxos Island, a group of factors were defined and various thematic maps were prepared and verified in the field. The factors that have been selected for this study were: a) the topographic slope, b) the lineaments density, c) the hydrolithology, d) the drainage density and e) the land cover of the study area. This selection was based on the characteristics of the hard rocks that indicate a suitability to hold groundwater and a high potentiality of water infiltration. The factors were divided into four categories, from low (index 0) to high potentiality of water infiltration (index 3) and were weighted according to AHP analysis, as seen in table I [12]. The category index of each factor was multiplied by the factor's weight and the final Groundwater Potential Index (GPI) derives from the addition of all the obtained values (Equation 1).

Factors	**Individual Features**	**Index**	**Weight (W_i)**
Slope (S)	0^o - 10^o	3	0.34
	10^o - 25^o	2	
	25^o - 45^o	1	
	> 45^o	0	
Lineaments density (LD)	Very low	0	0.31
	Low	1	
	Moderate	2	
	High	3	
Hydrolithology (HL)	Very low permeability	0	0.20
	Low permeability	1	
	Moderate permeability	2	
	High permeability	3	
Drainage density (DD)	Very low	3	0.10
	Low	2	
	Moderate	1	
	High	0	
Land cover / Landuse (LU)	Built up land	0	0.05
	Crop land	1	
	Grass land	2	
	Natural vegetation	3	

Table I identified features in each theme and weighted factors

$$GPI = 0{,}05 \cdot W_{LU} + 0{,}10 \cdot W_{DD} + 0{,}20 \cdot W_{HL} + 0{,}31 \cdot W_{LD} + 0{,}34 \cdot W_{S} \quad (1)$$

The information of lithology, geomorphology, lineaments, slope and land cover was generated by using topographical and geological map s of scale 1:50.000, land cover data from the Ministry of Agriculture of Greece, aerial photographs and a Landsat 7 ETM+ image of the stu dy area. The integration of all data was made in a raster based Geographical Information System (GIS), using the Spatial Analyst extension . Finally the FeFlow software was used in order to identify the groundwater potential zones based on the groundwater flow.

Analytically, one dataset of Landsat 7 ETM+ was subset and a combined satellite image of Naxos Island was produced with a resolution of 15m per pixel and 8 available spectral bands to combine. Also, a set of aerial photographs (1/30.000 scale) was orthorectified at the same projection and an orthophotomosaic was produced reaching a high resolution of 5 meters per pixel. The high and the low resolution i mages were merged resulted in an image which has the same spectral characteristics of Landsat 7, but better resolution. The new image was used for lineaments extraction and interpretation and a furthermore study was made for the density of the fractures [13]. Also, the dataset of Landsat 7 ETM+, together with the land cover data, were used for the identification of the land uses and t he vegetation of the study area.

It is known that satellite images in the red and the very near infrared wavelengths can be used for assessing the vegetation in an area, by computing a ratio known as Normalized Difference Vegetation Index - NDVI [14]. The principle behind the NDVI is that 'green' leaves absorb radiation at red wavelengths (640-670 nm) due to the presence of chlorophyll pigments whilst scattering radiance at very near infrared wavelengths (700-1100 nm) due to the internal structure of the leaf. In contrast a bare soil surface has higher reflectance at red wavelengths and lower reflectance at near-infrared wavelengths. NDVI is one of the most successful of many attempts to simply and quickly identify vegetated areas, and it remains the most well-known and used index to detect live green plant canopies in multispectral remote sensing data. Once the feasibility to detect vegetation had been demonstrated, users tended to also use the NDVI to quantify the pho to synthetic capacity of plant canopies.

Finally, the simulation of the groundwater flow in the hard rock hydrogeological environment has been made by using the software Feflow 6.1.

IV. GEOMORHOLOGY

For the estimation of the topographical slope in Naxos Island, a Digital Elevation Model (DEM) was used, which has been derived using contour information from topographical maps. In the constructed map (Fig. 3), it is possible to identify diverse geomorphological units. In the western lowland zone, which represents the 30% of the total area of the island, the terrain is gentle and the sedimentary formations are dominant. The terrain in the central and eastern part of the island has the greatest slopes, especially in the mountainous part of the island, where schists, marbles and migmatite are dominant [6].

As the topographical slope becomes steeper, the greater will be the runoff and thus, lesser the groundwater recharge, therefore this factor has the greatest weight.

V. LINEAMENTS DENSITY

Lineament mapping and specifically fault and fracture mapping is considered a very important issue for a hydrogeological research especially in hard rock environments, as the secondary porosity controls mainly the storage and movement of the groundwater. Lineament study of the area from remotely sensed data provides important information on subsurface permeability, as it is related with lineaments density.

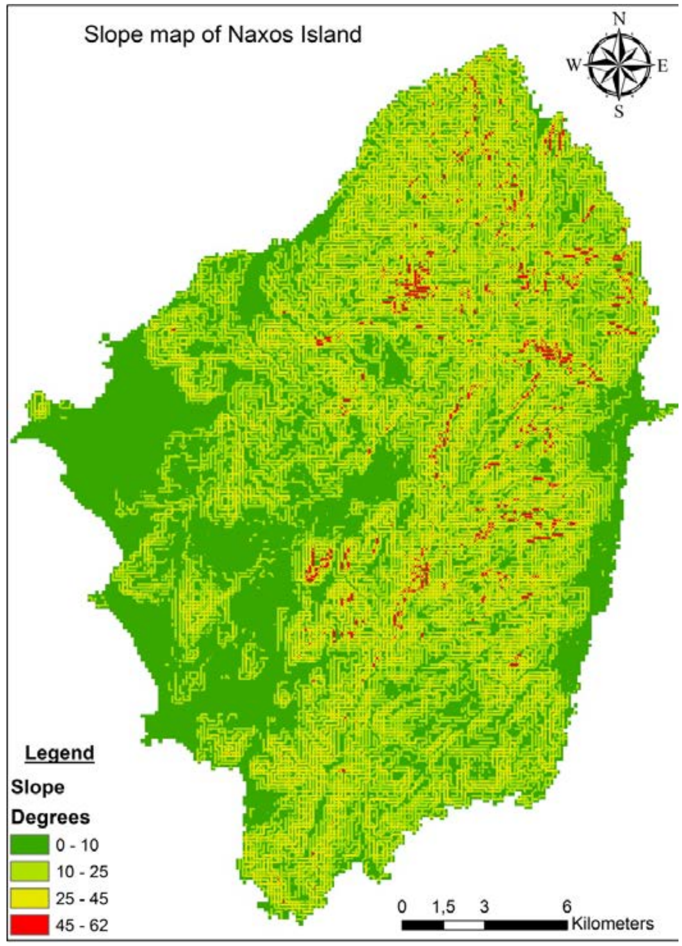

Fig. 3 slope map of Naxos island

The study area is crisscrossed by major and minor lineaments, which they vary in length from few meters to kilometers in dimension. Also, the lineaments rose plots indicated two sets of orientation classes. The three main classes have NNE-SSW, NE-SW and ENE-WSW strike, while the secondary ones have E-W and N-S strike [13].

The purpose of the fracture density analysis is to calculate frequency of the fractures per unit area. With this analysis a map has been produced showing concentrations of the lineaments over the study area (Fig. 4). The study revealed that very high density is observed in areas where the alternations between marbles, schists and amphibolites are very intense, citing the high degree of hydraulic interconnection between the above lithologic units as surface water circulates through these discontinuities. On the other hand, very low density is observed in granodiorites, post-alpine sediments and in areas where one lithology dominates. This verifies that these lithologies are not much affected by tectonic activity [13].

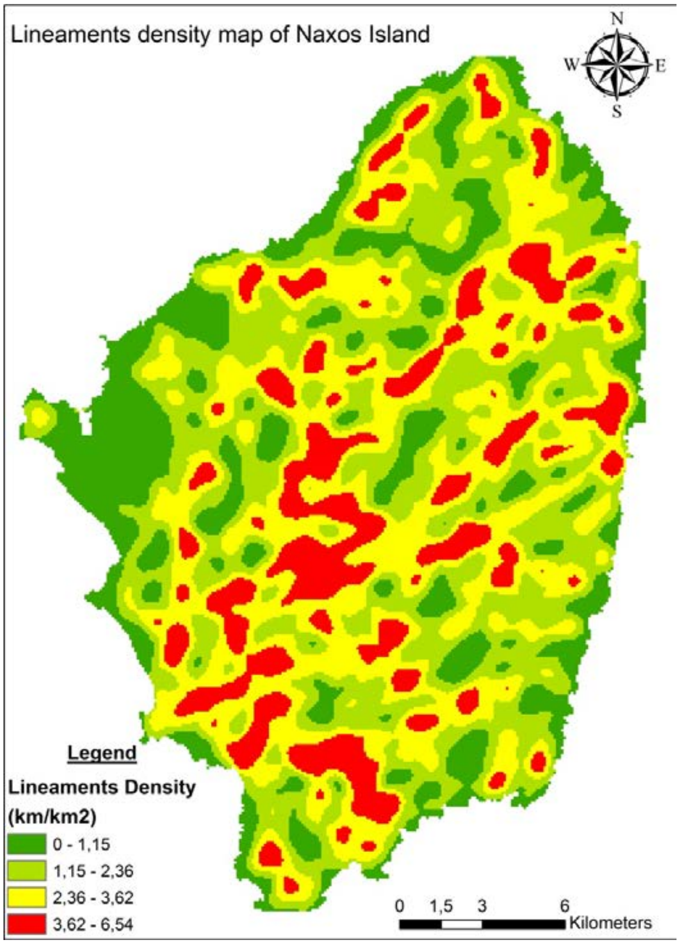

Fig. 4 lineaments density map of Naxos island

VI. HYDROLITHOLOGY

As it is already mentioned, the island of Naxos is consisted mainly by igneous and metamorphic rocks strongly welded. The hydrogeological behavior of these rocks in general is depended by the lithology, the porosity and the tectonic condition (number of discontinuities, cracks, etc.) and the hydrogeological environment in these cases is often characterized by the occurrence of local and shallow aquifers. The water impacts on the fractured media with a secondary process of dissolution and expansion of the fractures, contributing in turn to create favorable conditions for the underground flow [15].

This factor has been divided into four categories, from low (index 0) to high potentiality of water infiltration (index 3) according to the permeability of the lithological formations based on their primary porosity (for the sedimentary deposits), their secondary porosity (for the igneous and metamorphic rocks) and the tectonic structure. Lithologies such as granodiorites, schists and the migmatite are considered to have very low permeability compared to the sedimentary deposits of the upper non-metamorphic unit, which have very high permeability.

VII. DRAINAGE DENSITY

Drainage pattern reflects the characteristic of surface as well as the subsurface formation. Drainage density (in terms of km/km^2) indicates closeness of spacing of channels as well as the nature of the surface material. More the drainage density, higher would be runoff. Thus, the drainage density characterizes the runoff in the area or in other words, the quantum of relative rainwater that could have infiltrated. Hence lesser the drainage density, higher the probability of recharge or potential groundwater zone [5].

The distribution of the drainage density on the island of Naxos is asymmetric. The watersheds of the island of Naxos have a fairly large range of hydrographic density, due to the variety of lithological formations [13]. The largest hydrographic density values shown in the southern part of the island (Fig. 5).

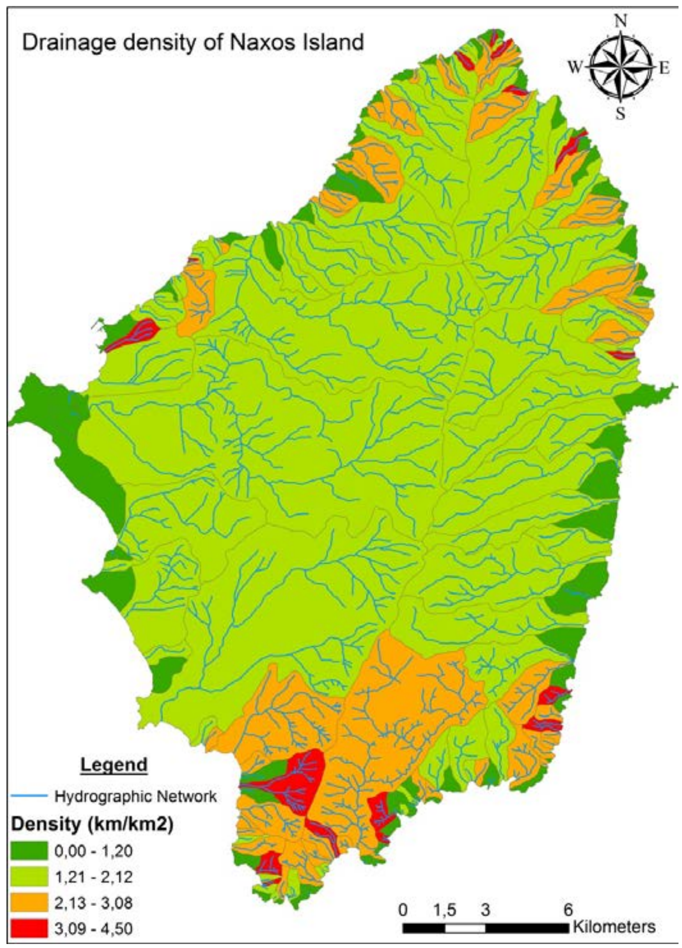

Fig. 5 drainage density map of Naxos island

VIII. LAND USES

The distribution of land uses is directly dependent on the topography of the island. Approximately 25% of the total area of the island is arable land, located mostly in the western lowlands. The rest of the area is covered by inaccessible areas with shrubs and scattered and unorganized grass lands. It should be noted that human interventions in the environment of Naxos is relatively limited compared with other islands with high tourism [6].

For the identification and interpretation of land use pattern of the study area, the standard methods of visual interpretation were adopted and the various land use classes delineated include build up land areas, crop land areas, grass land areas and areas with natural vegetation (Fig. 6).

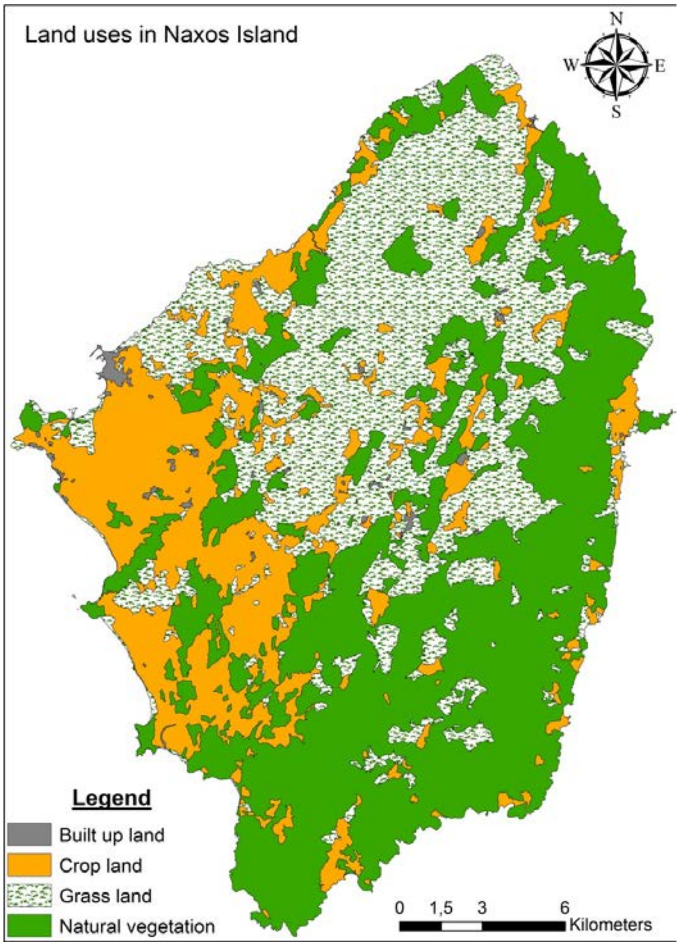

Fig. 6 land cover map of Naxos island

IX. Results

Each of the above thematic map (slope, lineaments density, hydrolithology, drainage density and land use) provides certain clue for the occurrence of groundwater. In order to get all of these information unified, an integration has been made through the application of GIS. These thematic maps were reclassified on the basis of weightage assigned an brought into the Raster Calculator function of Spatial Analyst tool for integration. Then the data were inserted into the Feflow software in order to define the groundwater flow. The final map has been categorized into four zones from groundwater potential point of view, according to the Groundwater Potential Index – GPI and the groundwater flow which was defined by the Feflow software. The extent of various zones in terms of area in km^2 is shown in Fig. 7.

The study area could be characterized by a low to moderate potentiality of groundwater presence, fact that is totally justified by the climatic and geologic conditions. Also, areas with high potentiality of groundwater presence are scattered in Naxos Island and they represent areas in which very high infiltration of water is occurred. These areas also must be studied further, as they may be suitable for extraction of potable water for rural populations.

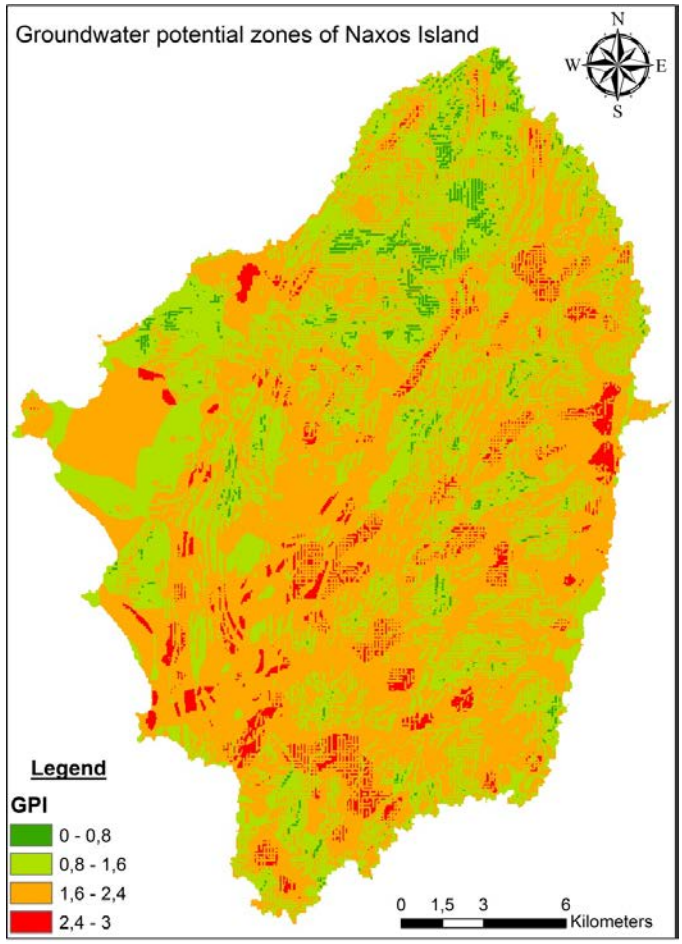

Fig. 7 groundwater potential zones of Naxos island

The groundwater potentiality was classified as very low, low, moderate and high, were the 58,37% of the island is characterized as moderate groundwater zone. The high potential zones occupy only the 4,65% of the total area and they are characterized by very gentle slopes, very high lineaments density, low drainage density, presence of vegetation and high permeability.

Finally, the simulation of the groundwater flow in the hard rock hydrogeological environment has been made, by using the climatic conditions, the potential zones (GPI) and the fracture pattern of the study area.

The results of the groundwater modeling are shown in Fig. 8 and Fig. 9, where the first one shows the hydraulic head at the beginning of the summer (May 2010), while the second one shows the hydraulic head in autumn (October 2010). A first result of the simulation is that the groundwater resources of the island are limited, as the aquifers are too deep and it is difficult to be exploited. Also, the differences for the five months of the simulation are evident, where the reduction of the hydraulic head is estimated at 60%. This massive reduction is justified by the extensive use of groundwater throughout the summer.

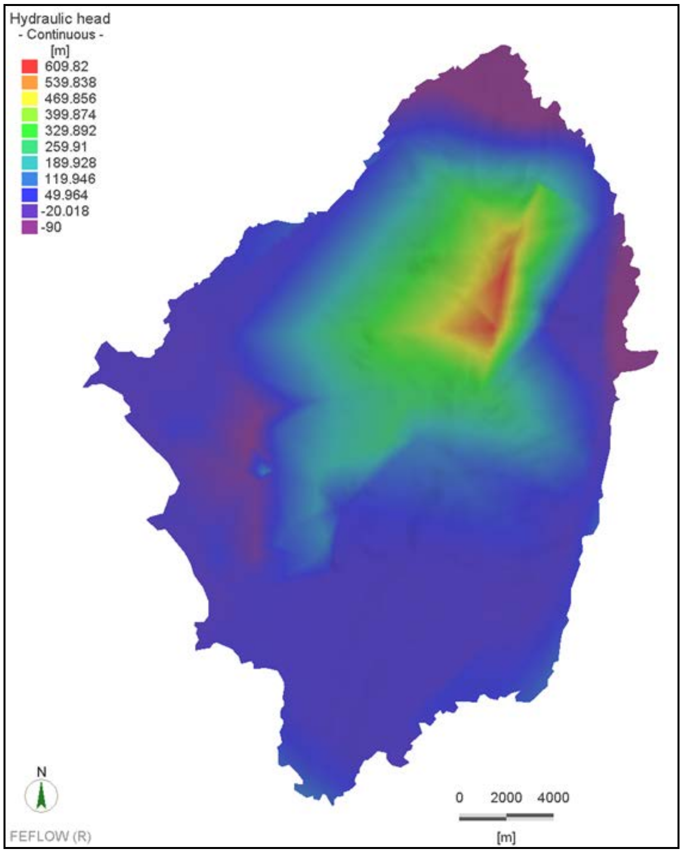

Fig. 8 simulated hydraulic head for May 2010.

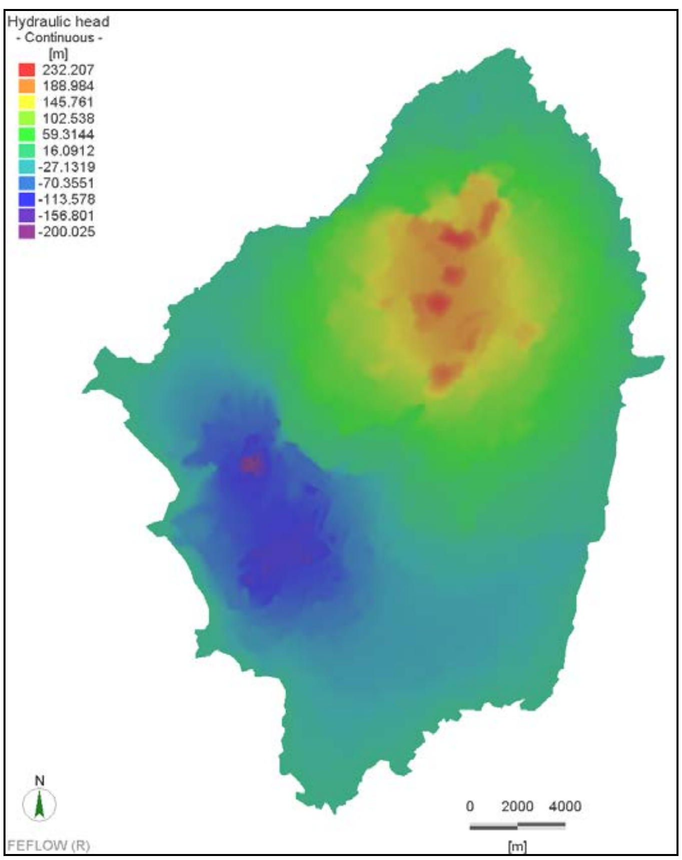

Fig. 9 simulated hydraulic head for October 2010.

X. Conclusions

In this study a GIS approach has been used to integrate various geoinformative thematic maps, which play major role in occurrence and movement of groundwater. The integrated groundwater potential map has been categorized on the basis of an AHP weightage assigned to different features of thematic maps. The integrated map thus deciphered could be useful for various purposes.

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Also, the results of the groundwater flow simulation show that the groundwater resources are extremely limited in the study area, while their extensive use throughout the summer could result serious water scarcity problems.

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